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Remanufacturing with trade-ins under carbon regulations

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ABSTRACT

Observing prevalent concerns about the influence of carbon emissions on climate change, we address the problem of remanufacturing with trade-ins under carbon regulations. We analyze the optimal pricing and production decisions of the manufacturer under the carbon tax policy and the cap and trade program. The results show that the introduction of carbon regulations can promote sales of remanufactured products while reducing the demands of new products. However, the implementation of carbon regulations has negative impacts on the manufacturer's profits. Nevertheless, the manufacturer's profits can be improved through deliberately designed government subsidy schemes. We also demonstrate that the government has the incentive to propose such subsidy schemes because the total emissions can be reduced under well-designed regulations, but not at the cost of the manufacturer's profits.

1. Introduction

Environmentally and socially sustainable operations have sprung up as a heated interest in the operations management literature in the last decade. In a recent survey paper, Tang and Zhou [28] point out that "consumers and governments are pressuring firms to strike a balance between profitability and sustainability." Remanufacturing has played an increasingly important role in sustainable operations because of its significant value in recovering used products. Through replacing or reprocessing used components from used products to produce "new" ones, remanufacturing can reduce the use of natural resources and waste in the production process, which helps enhance the environmental performances of the firms. However, remanufacturing is usually coupled with the problem of recycling used products. The processing of these used products often leads to waste streams for consumers but expands values for the manufacturer by remanufacturing or refurbishing. Trade-in programs provide a feasible method to solve this problem. In a trade-in program, the government offers an additional subsidy to consumers to compensate for the "residual value" of their existing products when they purchase new products and return used ones. Such practices have been widely observed. For example, the Chinese government proposed a trade-in subsidy policy for household appliances and automobiles to encourage consumers to purchase more energy-efficient new appliances or automobiles with their existing low-efficient used ones being returned in 2012. According to this policy, the total amount of subsidies can reach about \$43 billion.[1] In fact, trade-in programs have far more markets than are appreciated, ranging from golf clubs to CT scanners and also including bicycles, personal computers, and printers [25,24].

Although remanufacturing decisions have been discussed widely in the existent literature such as Ferrer et al. [7], Mitra [21], Atasu et al. [1], and Gong and Chao [9], there is rather limited research on the problem of remanufacturing with trade-in programs. The major difference between this problem and previous studies lies in the fact that the demand market of the former is constituted by *new consumers* and *replacement consumers*. In this case the purchases of new consumers are mainly determined by the manufacturer, while those of replacement consumers are also influenced by government subsidies. Remanufacturing and trade-in programs are closely related to carbon emissions that are becoming a common concern shared by governments, manufacturing firms, and many other stakeholders. In 2008 British Columbia first put carbon tax into practice in Canada, taking the bold step of introducing a broadly-based carbon tax to reduce carbon emissions [20]. In Europe many countries, such as Finland, Norway, Sweden, and Denmark, began to tax the emissions of carbon dioxide in

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[1] Based on public data from the State Council of China.

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the 1990s. With these governments' concerns about carbon emissions, some traditional operational problems are reconsidered in this context. Some important research includes Kroes et al. [14], Benjaafar et al. [3], Jira and Toffel [11], and Cachon [4]. These papers have made important steps to incorporate carbon concerns into operation management. However, despite its practical importance, remanufacturing with carbon regulations has not been considered by these studies.

Observing the prevailing applications of remanufacturing with trade-ins and the increasing importance of carbon emissions regulations, in this study, we consider remanufacturing with trade-ins under carbon emissions regulations. We intend to address a number of questions. For example, how does the manufacturer optimize its pricing and production decisions in this context? What are the influences of government regulations on the production decisions and profits of the manufacturer? By answering these questions we also provide useful managerial insights for both the manufacturers and the governments who are involved in trade-in programs and carbon emissions regulations. These insights may help both the manufacturers and the governments make informed decisions to achieve sustainability.

We consider remanufacturing and trade-in decisions of the firm under two types of commonly used carbon emissions regulations: carbon tax and “cap and trade” programs. The carbon tax policy mainly depends on the control of the government, while cap and trade also relies largely on the supply and demand relationship of the market. Due to the flexibility of the cap and trade mechanism, the European Union began the European Union emissions trading scheme in 2005 and covered the 27 countries of the European Union and three non-European Union members for now [27].

Through styled models we address the manufacturer's trade-in and remanufacturing decisions when the carbon emissions of the firm are limited and/or costly and reveal the influences these carbon regulations would have on the firm's optimal decisions and profits. Our results show that the firm's remanufacturing policy is determined by its remanufacturing cost and the government's subsidy when carbon regulations are absent. However in the presence of carbon emissions regulations, the remanufacturing policy is also dependent on the emissions cost, which is influenced by not only the firm itself but also the government's carbon instruments. Moreover, we find that the introduction of carbon regulations can boost the demands of remanufactured products under certain conditions even though they have negative effects on new products. In addition, generally the firm's profits are inevitably decreased under the carbon tax. However, the firm's profit loss due to emission costs can be compensated and even be more than offset by the compensation of government subsidies. We further demonstrate that the government has the incentive to implement such subsidy schemes because under certain conditions the subsidy can increase the firm's profits without increasing the firm's emission costs.

According to Tang and Zhou [28], firms have to pay more attention to the triple bottom-line dimensions—profit, people, and planet—when making their business decisions. This paper is closely related to the interface between the “profit” and the “planet” dimensions. In fact, the manufacturer needs to make pricing and production decisions to maximize its profit under the carbon regulations. In addition, the government also plays a significant role in these two dimensions because it has to consider the manufacturer's profitability and the environmental issues when developing subsidy schemes and carbon regulations.

The remainder of this paper is organized as follows: After Literature Review, we first formulate the demands and the base model in the third section. In Section 4, the models under the carbon tax and cap and trade are proposed and some main results about pricing policy, market demands and profits are also presented. In Section 5, we conclude the paper and offer some future research directions.

2. Literature review

In the sustainable operations management literature, this paper is related to three main streams of studies: remanufacturing, trade-ins, and carbon regulations. There is a large base of literature on remanufacturing. Atasu et al. [1] propose a complementary approach to consider several demand-related issues involving the existence of green segments, original equipment manufacturer competition, and product life-cycle effects. They provide the conditions that ensure the profitability of remanufacturing for a monopolist and demonstrate that the manufacturer can defend its market share via price discrimination where remanufacturing becomes an effective marketing strategy. Different from the marketing perspective, Ovchinnikov [23] is concerned with revenue and cost management of remanufactured products, and Geyer et al. [8] examine the economics of remanufacturing under limited component durability and finite product life cycle. Other studies also include the competition and cannibalization between new and remanufactured products [2,7], the match between demand and supply of remanufacturing [10], and product design with remanufacturing [29]. Some researchers employ the framework of multi-period dynamic production and inventory control problems to study remanufacturing (see, for example, [9] and the references therein). The aforementioned studies have provided significant contributions for understanding remanufacturing. Trade-in practices, however, have received limited attention. Rao et al. [24] incorporate key features of durable goods markets, such as the coexistence of new and used products markets and the cannibalization problem between them, heterogeneity of consumers, and the lemons problem in resale markets, to reveal the crucial role of trade-ins in durable goods markets. Kim et al. [13] focus on trade-in transactions and provide a model and empirical evidence on the preference of consumers for under- and overpayment. Some papers study trade-ins from the perspective of consumers; for example, Okada [22] incorporates mental accounting into the problem of trade-ins when consumers make product replacement decisions. Differently, Ray et al. [25] consider both trade-in rebates and remanufacturing in a durable products marketing. Assuming two distinct types of customers in the durable products market, the paper proposes the optimal pricing and trade-in strategies for such remanufacturable products and identifies the most favorable pricing strategy for the firm when faced with a particular market condition. In this paper we are also concerned with both trade-in and remanufacturing problems to identify different pricing and production strategies for different market conditions. However, the differences lie in the fact that we focus on joint decision-making concerning new and remanufactured products. On the other hand, in addition to the trade-in rebates as discussed in Ray et al. [25], we also explicitly consider the subsidies offered by the government. In this setting, we find that the firm's optimal pricing strategies and profits are not only affected by its own characteristics such as remanufacturing cost and emissions efficiency, but they also depend on the government's carbon regulations and subsidy schemes.

The last related stream of research is operations management under carbon regulations. This stream of research is relatively recent along with the heated global concerns on formulating or tightening regulations of carbon dioxide emissions to fight against climate change. Among these recent research works, Benjaafar et al. [3] have made an important contribution. Using relatively simple and widely used models, Benjaafar et al. [3] demonstrate how carbon emission concerns can be incorporated into operational decision making with regards to procurement, production, and

inventory management. They also point out that decision making that accounts for both cost and carbon footprint can be supported by modifying these traditional models. From the point of view of the supply chain, Cachon [4] redesigns the traditional supply chain by considering the cost of greenhouse gas emissions. Empirically, Kroes et al. [14] examine the relationships among levers for compliance, environmental performance, and firm market performance in the context of stringent cap and trade regulation. Related work is also presented by Jira and Toffel [11], who identify factors of sharing the information about a product's vulnerability to climate change from suppliers to buyers. Besides, regarding carbon regulations, Du et al. [6] investigate the influence of cap and trade on the game between upstream and downstream firms, and supply chain coordination by focusing on a so-called emission-dependent supply chain consisting of a single emission-dependent manufacturer and a single emission permit supplier in the cap and trade system. Some other studies explore the impacts of the carbon tax on the scheduling strategy [15] and the supplier selection problem [5]. The existing literature has made crucial contributions in revealing impacts of carbon emissions regulations on decision making of the firms. One basic result from this research is that the implementation of carbon regulations will generally hurt the firm's profits. This paper extends the models on remanufacturing by examining trade-in and remanufacturing strategies under carbon emissions regulations. We provide a number of managerial insights from the perspectives of both the firms and the governments. In particular, we demonstrate that the government can compensate the firms through subsidy schemes in the context of remanufacturing with trade-ins without increasing the total emissions.

3. The benchmark model without carbon regulations

We consider a monopolist providing new durable products and remanufactured products for the market to maximize its profits. There are two segments of customers in the market: the first-time buyers (new customers) and the replacement customers (trade-in customers). New buyers have not purchased products before and make purchase decisions according merely to the utilities they can obtain from the products, whereas the replacement customers who have owned products either (i) keep the existing products without purchasing any products or (ii) trade-in their existing products. The replacement customers also can simply buy a product without trade-in. This, however, is virtually the same as the purchase of new buyers and we consider this type of customer as a part of new buyers. Normalizing all customers in the market to one, we assume that there are α new customers and $1-\alpha$ replacement customers, where $0<\alpha<1$. These two customer segments act independently.

Both segments of customers make their purchase decisions based on the utilities associated with new and remanufactured products after observing the prices determined by the firm. Because both new and remanufactured products are available for the customers and are associated with different utilities, the customers are thus distinguished by their preferences between new and remanufactured products. As a result, pricing discrimination is adopted by the firm. We assume that consumers are heterogeneous with respect to their willingness-to-pay θ, which is uniformly distributed in $[0, 1]$. New customers value the new products at θ, while they value the remanufactured products lower at $\delta_r\theta$, where $0<\delta_r<1$. In the literature, some studies assume that the manufacturer aims to produce a remanufactured product that is indistinguishable from a "new product" (see for example, [12] and [9]). However, we assume that the remanufactured product is of less value. For example, it was reported that "Foxconn Technology Group has joined hands with Apple China on its 'reuse and recycling program'" [16]. Through this program, Apple is able to resell remanufactured iPhones at lower prices. This setting is also adopted in a number of recent studies on remanufacturing (see, for example, [1] and [7]). Given the new product price p_n and the remanufactured product price p_r, a new buyer gets a utility $U_n^n=\theta-p_n$ from the new product and a utility $U_r^n=\delta_r\theta-p_r$ from the remanufactured product. We assume $p_n>p_r$ and $p_n-p_r<1-\delta_r$, ruling out the impractical situation $p_n\le p_r$ and avoiding the trivial case with zero sales of new products. The new customer purchases the new product if $U_n^n>0$ and $U_n^n>U_r^n$. Otherwise, the new customer buys the remanufactured product if $U_r^n>0$.

For replacement customers, the salvage value of their existing products is denoted as $\delta_o\theta$, where $0<\delta_o<\delta_r$. This segment of customers purchases the products only if the utility associated with purchase is not less than their reservation utility, i.e., $\delta_o\theta$. The usage of old energy-inefficient products causes more environmental problems than do new products. Consequently, the government often encourages people to replace their existing dated-technology products. To reflect this, we assume that the government offers a subsidy s for each replacement. The remanufacturing firm can also benefit from this policy through increased sales from new and remanufactured products and profits from recycling old products or reselling them to other recycling firms. Given the new product price p_n, the remanufactured product price p_r, the trade-in rebate p_o, and the subsidy s from the government, a replacement customer can get utility $U_n^o=\theta-p_n+p_o+s$ from the new product and utility $U_r^o=\delta_r\theta-p_r+p_o+s$ from the remanufactured product. The replacement customer chooses the new product if $U_n^o>\delta_o\theta$ and $U_n^o>U_r^o$. Otherwise, the replacement customer purchases the remanufactured product if $U_r^o>\delta_o\theta$.

3.1. Demand

For first-time buyers, the choice between the new products and the remanufactured products depends on the pricing strategies of the manufacturer. When the manufacturer sets a low price for the remanufactured products (i.e., $p_r\le\delta_r p_n$), new customers may obtain positive utilities from both the new and the remanufactured products. To see this, we notice that new customers buy the remanufactured products if $U_r^n>0$ and $U_r^n>U_n^n$, which implies $p_r<\delta_r p_n$. Furthermore, when $p_r\le\delta_r p_n$, we can easily obtain that new customers with high willingness to pay generate the demand for new products, which is denoted as

$$Q_n^n=\alpha\left(1-\frac{p_n-p_r}{1-\delta_r}\right).$$

The demand of the remanufactured products comes from the price-sensitive new customers and is given by

$$Q_r^n=\alpha\left(\frac{p_n-p_r}{1-\delta_r}-\frac{p_r}{\delta_r}\right)=\frac{\alpha(\delta_r p_n-p_r)}{\delta_r(1-\delta_r)}.$$

When the manufacturer sets a high price for remanufactured products (i.e., $p_r>\delta_r p_n$), all new customers will purchase the new products. Thus, the demand of the new products is

$$Q_n^n=\alpha(1-p_n),$$

and the demand for remanufactured products is $Q_r^n=0$ because $U_n^n>U_r^n$.

Similarly, for replacement customers, the demands for the new and the remanufactured products depend on the firm's pricing decisions. However, the pricing decisions in this case become more complicated because the manufacturer has to determine the new product price p_n, the remanufactured product price p_r, and

the trade-in rebate p_o. To facilitate our discussion, define $\Delta = (\delta_r - \delta_o)p_n - (1-\delta_o)p_r + (1-\delta_r)(p_o+s)$. We consider two pricing scenarios: $\Delta \geq 0$ and $\Delta < 0$. When $\Delta \geq 0$, the demand for the new products comes from replacement customers with a high willingness-to-pay:

$$Q_n^o = (1-\alpha)\left(1 - \frac{p_n - p_r}{1-\delta_r}\right).$$

The price-sensitive replacement customers will purchase the remanufactured products and their demand can be expressed as

$$\begin{aligned} Q_r^o &= (1-\alpha)\left(\frac{p_n - p_r}{1-\delta_r} - \frac{p_r - p_o - s}{\delta_r - \delta_o}\right) \\ &= (1-\alpha)\frac{(\delta_r - \delta_o)p_n - (1-\delta_o)p_r + (1-\delta_r)(p_o+s)}{(\delta_r-\delta_o)(1-\delta_r)}. \end{aligned}$$

When $\Delta < 0$, all the replacement customers prefer new products because they always can obtain higher utilities from new products. In this case, the demand of the new products is

$$Q_n^o = (1-\alpha)\left(1 - \frac{p_n - p_o - s}{1-\delta_o}\right)$$

and the demand for remanufactured products is $Q_r^o = 0$.

3.2. Basic model

As a benchmark model, we first discuss the manufacturer's optimization problem without carbon regulations. Consider that the manufacturer provides a new product with a unit production cost c_n and a remanufactured product with a unit production cost c_r with an unconstrained remanufacturable product supply. That is, we assume that a third party is responsible for collecting used products and sells these returned products to the manufacturer. A number of research papers also adopt this assumption, see, for example, Mitra [21], Atasu et al. [1], and Ovchinnikov [23]. It is also common in practice. For example, Mazuma [17] is such a third party recycling used cell phones. Uncertainties surrounding the quality of returned products may be an important factor for remanufacturing (see, for example, [10] and [21]), however, to obtain tractable results, we assume that the quality of the returned items used for remanufacturing is guaranteed, which is similar to Atasu et al. [1] and Ovchinnikov [23].

The old products collected by the manufacturer are either remanufactured or resold to other recycling firms. We assume that the unit salvage of the old products is a constant denoted by ν. To maximize the total profit from both the new and the remanufactured products, the manufacturer solves the following nonlinear optimization problem:

$$\begin{aligned} \max \quad \pi(p_n, p_r, p_o) = (p_n - c_n)(Q_n^n + Q_n^o) + (p_r - c_r)(Q_r^n + Q_r^o) \\ - (p_o - \nu)(Q_n^o + Q_r^o) \end{aligned} \tag{1}$$

$$\text{s.t.} \quad \begin{cases} Q_n^n \geq 0 \\ Q_n^o \geq 0 \\ Q_r^n \geq 0 \\ Q_r^o \geq 0 \end{cases} \tag{2}$$

The demands for the new and the remanufactured products are summarized in Table 1. For simplicity, we define four market scenarios: market scenario NR, market scenario N, market scenario R, and market scenario O. They denote respectively the scenario that the remanufacturing product demands come from both new customers and replacement customers, only new customers, only replacement customers and neither new customers nor replacement customers. The notation for the four market scenarios will be used throughout the paper. It is worth noting that under different regulations, the conditions that distinguish these market scenarios may be different. These demands are discriminated by the supply of remanufactured products between the new and the replacement market. That is, all customers will only purchase new products when the price of the remanufactured products is sufficiently high; otherwise, demands for both the new and the remanufactured products will be generated. To solve these optimization problems in different scenarios, we first provide the manufacturer's optimal pricing policies in the following proposition.

Proposition 1. *The manufacturer's optimal pricing policies can be described as follows*:

(i) *When* $\delta_r c_n \geq c_r$ *and* $(\delta_r - \delta_o)c_n - (1-\delta_o)c_r + (1-\delta_r)(\nu + s) \geq 0$, *the remanufactured products are supplied in both the new market and the replacement market. The manufacturer's pricing policy is* $p_n^* = (1+c_n)/2$, $p_r^* = (\delta_r + c_r)/2$ *and* $p_o^* = (\delta_o + \nu - s)/2$.

(ii) *When* $\delta_r c_n < c_r$ *and* $(\delta_r - \delta_o)c_n - (1-\delta_o)c_r + (1-\delta_r)(\nu + s) \geq 0$, *the remanufactured products are only supplied in the replacement market, while if* $\delta_r c_n \geq c_r$ *and* $(\delta_r - \delta_o)c_n - (1-\delta_o)c_r + (1-\delta_r)(\nu + s) < 0$, *they are supplied only in the new market. In both of these two scenarios, the manufacturer's pricing policy is* $p_n^* = (1+c_n)/2$, $p_r^* = (\delta_r + c_r)/2$ *and* $p_o^* = (\delta_o + \nu - s)/2$.

Table 1
Demands of the new and remanufactured products under different conditions.

Conditions	$\Delta \geq 0$	$\Delta < 0$
$p_r \leq \delta_r p_n$	$Q_n^n = \alpha\left(1 - \frac{p_n - p_r}{1-\delta_r}\right)$	$Q_n^n = \alpha\left(1 - \frac{p_n - p_r}{1-\delta_r}\right)$
	$Q_r^n = \frac{\alpha(\delta_r p_n - p_r)}{\delta_r(1-\delta_r)}$	$Q_r^n = \frac{\alpha(\delta_r p_n - p_r)}{\delta_r(1-\delta_r)}$
	$Q_n^o = (1-\alpha)\left(1 - \frac{p_n - p_r}{1-\delta_r}\right)$	$Q_n^o = (1-\alpha)(1 - \frac{p_n - p_o - s}{1-\delta_o})$
	$Q_r^o = (1-\alpha)\frac{(\delta_r-\delta_o)p_n - (1-\delta_o)p_r + (1-\delta_r)(p_o+s)}{(\delta_r-\delta_o)(1-\delta_r)}$	$Q_r^o = 0$
$p_r > \delta_r p_n$	$Q_n^n = \alpha(1-p_n)$	$Q_n^n = \alpha(1-p_n)$
	$Q_r^n = 0$	$Q_r^n = 0$
	$Q_n^o = (1-\alpha)\left(1 - \frac{p_n - p_r}{1-\delta_r}\right)$	$Q_n^o = (1-\alpha)\left(1 - \frac{p_n - p_o - s}{1-\delta_o}\right)$
	$Q_r^o = (1-\alpha)\frac{(\delta_r-\delta_o)p_n - (1-\delta_o)p_r + (1-\delta_r)(p_o+s)}{(\delta_r-\delta_o)(1-\delta_r)}$	$Q_r^o = 0$

(iii) *When* $\delta_r c_n < c_r$ *and* $(\delta_r - \delta_o)c_n - (1-\delta_o)c_r + (1-\delta_r)(\nu + s) < 0$, *the remanufactured products are neither supplied in the new market nor in the replacement market. The manufacturer's pricing policy is* $p_n^* = (1+c_n)/2$ *and* $p_o^* = (\delta_o + \nu - s)/2$.

Proof. To solve problem (1)–(2), we consider the four sub-problems shown in Table 1. Solving these four sub-problems is equivalent to solving the original problem with non-negative constraints.

(i) When $p_r \le \delta_r p_n$ and $\Delta \ge 0$,

$$Q_n^n = \alpha\left(1 - \frac{p_n - p_r}{1-\delta_r}\right), \quad Q_r^n = \frac{\alpha(\delta_r p_n - p_r)}{\delta_r(1-\delta_r)},$$
$$Q_n^o = (1-\alpha)\left(1 - \frac{p_n - p_r}{1-\delta_r}\right),$$

and

$$Q_r^o = (1-\alpha)\frac{(\delta_r - \delta_o)p_n - (1-\delta_o)p_r + (1-\delta_r)(p_o + s)}{(\delta_r - \delta_o)(1-\delta_r)}.$$

Substituting them into the profit function and taking derivatives, we have

$$\begin{aligned}
\frac{\partial\pi(p_n,p_r,p_o)}{\partial p_n} &= 1 - \frac{p_n - p_r}{1-\delta_r} - \frac{p_n - c_n}{1-\delta_r} + \frac{p_r - c_r}{1-\delta_r}; \frac{\partial\pi(p_n,p_r,p_o)}{\partial p_r}\\
&= \frac{p_n - c_n}{1-\delta_r} + \frac{p_n}{1-\delta_r} - \frac{(1-\delta_o)p_r}{(\delta_r-\delta_o)(1-\delta_r)} + \frac{\alpha\delta_o p_r}{(\delta_r-\delta_o)\delta_r}\\
&\quad + \frac{(1-\alpha)(p_o+s)}{\delta_r-\delta_o} - \frac{(1-\delta_o)(p_r-c_r)}{(\delta_r-\delta_o)(1-\delta_r)}\\
&\quad + \frac{\alpha\delta_o(p_r-c_r)}{(\delta_r-\delta_o)\delta_r} + \frac{(p_o-\nu)(1-\alpha)}{\delta_r-\delta_o}\\
&= \frac{p_n-c_n}{1-\delta_r} + \frac{p_n}{1-\delta_r} - \frac{p_r}{\delta_r-\delta_o} - \frac{p_r}{1-\delta_r} - \frac{p_r-c_r}{\delta_r-\delta_o}\\
&\quad - \frac{p_r-c_r}{1-\delta_r} + \frac{\alpha\delta_o p_r}{(\delta_r-\delta_o)\delta_r} + \frac{(1-\alpha)(p_o+s)}{\delta_r-\delta_o}\\
&\quad + \frac{\alpha\delta_o(p_r-c_r)}{(\delta_r-\delta_o)\delta_r} + \frac{(p_o-\nu)(1-\alpha)}{\delta_r-\delta_o}; \frac{\partial\pi(p_n,p_r,p_o)}{\partial p_o}\\
&= \frac{(1-\alpha)(p_r-c_r)}{\delta_r-\delta_o} - \frac{(1-\alpha)(p_o-\nu)}{\delta_r-\delta_o}\\
&\quad - \left[1-\alpha - \frac{(1-\alpha)(p_r-p_o-s)}{\delta_r-\delta_o}\right].
\end{aligned}$$

Setting $\frac{\partial\pi}{\partial p_n}=0$, $\frac{\partial\pi}{\partial p_r}=0$ and $\frac{\partial\pi}{\partial p_o}=0$, solving these three equations, we can obtain the optimal price strategies of the firm as follows:

$$p_n^* = \frac{1+c_n}{2}, \quad p_r^* = \frac{\delta_r + c_r}{2}, \quad p_o^* = \frac{\delta_o + \nu - s}{2}.$$

The determinant of the Hessian is positive. Thus, these solutions derived from the first order conditions give the unique maximizer. To ensure $p_r^* \le \delta_r p_n^*$ and $\Delta \ge 0$, we have $\delta_r c_n \ge c_r$ and $(\delta_r - \delta_o)c_n - (1-\delta_o)c_r + (1-\delta_r)(\nu+s) \ge 0$.

(ii) When $p_r \le \delta_r p_n$ and $\Delta < 0$,

$$Q_n^n = \alpha\left(1 - \frac{p_n - p_r}{1-\delta_r}\right), \quad Q_r^n = \frac{\alpha(\delta_r p_n - p_r)}{\delta_r(1-\delta_r)},$$
$$Q_n^o = (1-\alpha)\left(1 - \frac{p_n - p_o - s}{1-\delta_o}\right), \quad Q_r^o = 0.$$

Taking derivatives, we have

$$\begin{aligned}
\frac{\partial\pi(p_n,p_r,p_o)}{\partial p_n} &= 1 - \frac{p_n-p_r}{1-\delta_r}\alpha - \frac{p_n-p_o-s}{1-\delta_o}(1-\alpha) - (p_n-c_n)\\
&\quad \times\left(\frac{\alpha}{1-\delta_r} + \frac{1-\alpha}{1-\delta_o}\right) + (p_r-c_r)\frac{\alpha}{1-\delta_r} + (p_o-\nu)\\
&\quad \frac{1-\alpha}{1-\delta_o},\\
\frac{\partial\pi(p_n,p_r,p_o)}{\partial p_r} &= (p_n-c_n)\frac{\alpha}{1-\delta_r} + \frac{\alpha(\delta_r p_n - p_r)}{\delta_r(1-\delta_r)} - (p_r-c_r)\frac{\alpha}{\delta_r(1-\delta_r)},\\
\frac{\partial\pi(p_n,p_r,p_o)}{\partial p_o} &= (p_n-c_n)\frac{1-\alpha}{1-\delta_o} - (1-\alpha)\left(1 - \frac{p_n-p_o-s}{1-\delta_o}\right)\\
&\quad - (p_o-\nu)\frac{1-\alpha}{1-\delta_o}.
\end{aligned}$$

Setting $\frac{\partial\pi}{\partial p_n}=0$, $\frac{\partial\pi}{\partial p_r}=0$ and $\frac{\partial\pi}{\partial p_o}=0$, we can obtain the optimal price strategies of the firm as follows:

$$p_n^* = \frac{1+c_n}{2}, \quad p_r^* = \frac{\delta_r + c_r}{2}, \quad p_o^* = \frac{\delta_o + \nu - s}{2}.$$

The determinant of the Hessian is positive. Then, the solutions derived from the first order conditions give the unique maximizer. To ensure $p_r^* \le \delta_r p_n^*$ and $\Delta < 0$, we have $\delta_r c_n \ge c_r$ and $(\delta_r - \delta_o)c_n - (1-\delta_o)c_r + (1-\delta_r)(\nu+s) < 0$.

Analogously, when $p_r > \delta_r p_n$ and $\Delta \ge 0$, we can have the first order condition and derive the pricing strategies as

$$p_n^* = \frac{1+c_n}{2}, \quad p_r^* = \frac{\delta_r + c_r}{2}, \quad p_o^* = \frac{\delta_o + \nu - s}{2}.$$

The associated conditions are $\delta_r c_n < c_r$ and $(\delta_r - \delta_o)c_n - (1-\delta_o)c_r + (1-\delta_r)(\nu+s) \ge 0$.

(iii) when $p_r > \delta_r p_n$ and $\Delta < 0$,

$$Q_n^n = \alpha(1-p_n), \quad Q_r^n = 0, \quad Q_n^o = (1-\alpha)\left(1 - \frac{p_n-p_o-s}{1-\delta_o}\right), \quad Q_r^o = 0.$$

Taking derivatives, we have

$$\begin{aligned}
\frac{\partial\pi(p_n,p_r,p_o)}{\partial p_n} &= \alpha(1-p_n) + (1-\alpha)\left(1 - \frac{p_n-p_o-s}{1-\delta_o}\right)\\
&\quad - (p_n-c_n)\left(\alpha + \frac{1-\alpha}{1-\delta_o}\right) + (p_o-\nu)\frac{1-\alpha}{1-\delta_o},\\
\frac{\partial\pi(p_n,p_r,p_o)}{\partial p_o} &= (p_n-c_n)\frac{1-\alpha}{1-\delta_o} - (1-\alpha)\left(1 - \frac{p_n-p_o-s}{1-\delta_o}\right)\\
&\quad - (p_o-\nu)\frac{1-\alpha}{1-\delta_o}.
\end{aligned}$$

Let $\frac{\partial\pi}{\partial p_n}=0$, $\frac{\partial\pi}{\partial p_r}=0$ and $\frac{\partial\pi}{\partial p_o}=0$, we derive the optimal price strategies as

$$p_n^* = \frac{1+c_n}{2}, \quad p_o^* = \frac{\delta_o + \nu - s}{2}.$$

The determinant of the Hessian is positive. Then, the solutions derived from the first order conditions give the unique maximizer. To ensure $p_r^* > \delta_r p_n^*$ and $\Delta < 0$, we have $\delta_r c_n < c_r$ and $(\delta_r - \delta_o)c_n - (1-\delta_o)c_r + (1-\delta_r)(\nu+s) < 0$. □

Note that in general one may need to apply KKT conditions to solve nonlinear optimization problems with constraints. However, in the proof of Proposition 1, we use the observation that the optimization problem can be decomposed into four sub-problems. For each sub-problem, it suffices to solve an unconstrained problem. Solving these four sub-problems is equivalent to solving the original problem. According to the above proposition, the manufacturer's production decisions depend on the cost structure of the new and remanufactured products, the salvage value of the old products, and the subsidy from the government. In the new

product market, a low remanufacturing cost can urge the firm to provide the remanufactured products, thereby capturing the demands of price-sensitive customers. However, with trade-ins, the demand in the replacement market is also affected by the characteristics of the old products, such as the trade-in value for customers, the salvage value for the manufacturer, and the subsidy policy of the government. Thus, the government can also affect the production planning of the manufacturer by providing certain trade-in subsidy schemes for customers. In addition, the proposition suggests that producing only new products and ignoring the replacement market may lead to suboptimal solutions. Furthermore, the optimal prices of new products and the trade-in rebate in different scenarios are the same, which indicates that the optimal pricing for new products and rebating strategy for trade-ins are independent of the decisions of remanufactured products and recycled products. This is because we assume that the supply of remanufactured products is unlimited and is not affected by the products collected through trade-ins, although the collected products can be used in remanufacturing. These results are insightful for the manufacturer because it can determine its pricing policies without considering the specific composition of the market.

Notably, according to the expression $p_o^* = (\delta_o + v - s)/2$, the value of p_o^* can be negative when $s > \delta_o + v$. That is, if the salvage value of existing products for consumers is low (i.e., the value δ_o is low) or the value of the old products is not significant for the firm (i.e., the value of v is low) or both, consumers should pay a certain amount of money to the firm. This makes sense as many government regulations have been put into force to charge for waste disposal. In fact, under this situation, p_o^* can be regarded as handling charges of old products. In addition, when the subsidy from the government is high enough so that $s > \delta_o + v$, the firm is also able to extract profits from consumers for their old products.

Based on Proposition 1, we can present the optimal production quantities of the new and the remanufactured products. The proposition demonstrates the manufacturer's production policies when faced with different cost advantages. Let Q_N^{i*} denote the total demand of new products in the new market and the replacement market and Q_R^{i*} denote the total demand of remanufactured products in the new market and the replacement market for $i = NR, N, R, O$.

Proposition 2. *The demands of the new products and remanufactured products under the optimal pricing policies can be expressed as follows*:

Condition	$(1-\delta_r)(v+s) \geq (1-\delta_o)c_r - (\delta_r-\delta_o)c_n$	$(1-\delta_r)(v+s) < (1-\delta_o)c_r - (\delta_r-\delta_o)c_n$
$c_r \leq \delta_r c_n$	$Q_n^{nNR*} = \frac{\alpha}{2}\left[1 - \frac{(c_n-c_r)}{1-\delta_r}\right]$	$Q_n^{nN*} = \frac{\alpha}{2}\left[1 - \frac{(c_n-c_r)}{1-\delta_r}\right]$
	$Q_r^{nNR*} = \frac{\alpha(\delta_r c_n - c_r)}{2\delta_r(1-\delta_r)}$	$Q_r^{nN*} = \frac{\alpha(\delta_r c_n - c_r)}{2\delta_r(1-\delta_r)}$
	$Q_n^{oNR*} = \frac{(1-\alpha)}{2}\left[1 - \frac{(c_n-c_r)}{1-\delta_r}\right]$	$Q_n^{oN*} = \frac{(1-\alpha)}{2}\left(1 - \frac{c_n}{1-\delta_0}\right) + \frac{(1-\alpha)(v+s)}{2(1-\delta_o)}$
	$Q_r^{oNR*} = \frac{(1-\alpha)[(\delta_r-\delta_o)c_n - (1-\delta_o)c_r]}{2(\delta_r-\delta_o)(1-\delta_r)} + \frac{(1-\alpha)(v+s)}{2(\delta_r-\delta_o)}$	$Q_r^{oN*} = 0$
$c_r > \delta_r c_n$	$Q_n^{nR**} = \frac{\alpha(1-c_n)}{2}$	$Q_n^{nO*} = \frac{\alpha(1-c_n)}{2}$
	$Q_r^{nR*} = 0$	$Q_r^{nO*} = 0$
	$Q_n^{oR*} = \frac{(1-\alpha)}{2}\left[1 - \frac{(c_n-c_r)}{1-\delta_r}\right]$	$Q_n^{oO*} = \frac{(1-\alpha)}{2}\left(1 - \frac{c_n}{1-\delta_0}\right) + \frac{(1-\alpha)(v+s)}{2(1-\delta_o)}$
	$Q_r^{oR*} = \frac{(1-\alpha)[(\delta_r-\delta_o)c_n - (1-\delta_o)c_r]}{2(\delta_r-\delta_o)(1-\delta_r)} + \frac{(1-\alpha)(v+s)}{2(\delta_r-\delta_o)}$	$Q_r^{oO*} = 0$

Proof. According to Proposition 1, the optimal price strategies are

$$p_n^* = \frac{1+c_n}{2}, \quad p_r^* = \frac{\delta_r + c_r}{2}, \quad p_o^* = \frac{\delta_o + v - s}{2}.$$

Substitute the optimal prices into demand function, for scenario NR, we have

$$\begin{aligned} Q_n^{nNR*} &= \alpha\left(1 - \frac{p_n^* - p_r^*}{1-\delta_r}\right) = \frac{\alpha}{2}\left[1 - \frac{(c_n-c_r)}{1-\delta_r}\right]; Q_r^{nNR*} = \frac{\alpha(\delta_r p_n^* - p_r^*)}{\delta_r(1-\delta_r)} \\ &= \frac{\alpha(\delta_r c_n - c_r)}{2\delta_r(1-\delta_r)}; Q_n^{oNR*} = (1-\alpha)\left(1 - \frac{p_n^* - p_r^*}{1-\delta_r}\right) \\ &= \frac{(1-\alpha)}{2}\left[1 - \frac{(c_n-c_r)}{1-\delta_r}\right]; Q_r^{oNR*} \\ &= (1-\alpha)\frac{(\delta_r-\delta_o)p_n^* - (1-\delta_o)p_r^* + (1-\delta_r)(p_o^*+s)}{(\delta_r-\delta_o)(1-\delta_r)} \\ &= \frac{(1-\alpha)[(\delta_r-\delta_o)c_n - (1-\delta_o)c_r]}{2(\delta_r-\delta_o)(1-\delta_r)} + \frac{(1-\alpha)(v+s)}{2(\delta_r-\delta_o)}. \end{aligned}$$

For scenario N, we have

$$\begin{aligned} Q_n^{nN*} &= \alpha\left(1 - \frac{p_n^* - p_r^*}{1-\delta_r}\right) = \frac{\alpha}{2}\left[1 - \frac{(c_n-c_r)}{1-\delta_r}\right]; Q_r^{nN*} = \frac{\alpha(\delta_r p_n^* - p_r^*)}{\delta_r(1-\delta_r)} \\ &= \frac{\alpha(\delta_r c_n - c_r)}{2\delta_r(1-\delta_r)}; Q_n^{oN*} = (1-\alpha)\left(1 - \frac{p_n^* - p_o^* - s}{1-\delta_o}\right) \\ &= \frac{(1-\alpha)}{2}\left(1 - \frac{c_n}{1-\delta_0}\right) + \frac{(1-\alpha)(v+s)}{2(1-\delta_o)}; Q_r^{oN*} = 0. \end{aligned}$$

For scenario R, we can derive

$$
\begin{aligned}
Q_n^{nR*} &= \alpha(1-p_n^*) = \frac{\alpha(1-c_n)}{2}; Q_r^{nR*} = 0; Q_n^{oR*} \\
&= (1-\alpha)\left(1 - \frac{p_n^* - p_r^*}{1-\delta_r}\right) = \frac{(1-\alpha)}{2}\left[1 - \frac{(c_n - c_r)}{1-\delta_r}\right]; Q_r^{oR*} \\
&= (1-\alpha)\frac{(\delta_r - \delta_o)p_n^* - (1-\delta_o)p_r^* + (1-\delta_r)(p_o^* + s)}{(\delta_r - \delta_o)(1-\delta_r)} \\
&= \frac{(1-\alpha)[(\delta_r - \delta_o)c_n - (1-\delta_o)c_r]}{2(\delta_r - \delta_o)(1-\delta_r)} + \frac{(1-\alpha)(v+s)}{2(\delta_r - \delta_o)}.
\end{aligned}
$$

For scenario O, it is easy to show

$$
\begin{aligned}
Q_n^{nO*} &= \alpha(1-p_n^*) = \frac{\alpha(1-c_n)}{2}; Q_r^{nO*} = 0; Q_n^{oO*} \\
&= (1-\alpha)\left(1 - \frac{p_n^* - p_o^* - s}{1-\delta_o}\right) \\
&= \frac{(1-\alpha)}{2}\left(1 - \frac{c_n}{1-\delta_0}\right) + \frac{(1-\alpha)(v+s)}{2(1-\delta_o)}; Q_r^{oO*} = 0.
\end{aligned}
$$

The proof is complete. □

This proposition indicates that, for a given subsidy s, the manufacturer's production policies are subject to the tradeoff between the cost of the new products and that of the remanufactured products. The cost structures of the new and the remanufactured products determine the production quantities of the two products, whereas the subsidy of the government further influences the distribution of the products between the new market and the replacement market.

In scenario NR, both the new and the remanufactured products are provided in the new market and the replacement market. However in scenario N and scenario R, the remanufactured products are available only in one market although the new products are provided in both markets. In particular, in scenario N, the manufacturer produces the remanufactured products only for the new market and covers the replacement market with the new products due to the low subsidy. In scenario R, the remanufactured products are present only in the replacement market, and the new market is satisfied only by the new products due to the high remanufacturing cost. As for scenario O, both the new market and the replacement market are covered by the new products only and the manufacturer does not choose remanufacturing because of the high remanufacturing cost and low subsidy.

Corollary 1. *Suppose that c_r and c_n are fixed, then if $c_r \le \delta_r c_n$ we have*

(i) *when* $(1-\delta_r)(s+v) \ge (1-\delta_o)c_r - (\delta_r - \delta_o)c_n$, $\partial Q_N^{NR*}/\partial s = 0$ *and* $\partial Q_R^{NR*}/\partial s > 0$; *when* $(1-\delta_r)(s+v) < (1-\delta_o)c_r - (\delta_r - \delta_o)c_n$, $\partial Q_N^{N*}/\partial s > 0$ *and* $\partial Q_R^{N*}/\partial s = 0$;

otherwise if $c_r > \delta_r c_n$, *we have*

(ii) *when* $(1-\delta_r)(s+v) \ge (1-\delta_o)c_r - (\delta_r - \delta_o)c_n$, $\partial Q_N^{R*}/\partial s = 0$ *and* $\partial Q_R^{R*}/\partial s > 0$; *when* $(1-\delta_r)(s+v) < (1-\delta_o)c_r - (\delta_r - \delta_o)c_n$, $\partial Q_N^{O*}/\partial s > 0$ *and* $\partial Q_R^{O*}/\partial s = 0$;

where $Q_N^{i*} = Q_n^{ni*} + Q_n^{oi*}$ *and* $Q_R^{i*} = Q_r^{ni*} + Q_r^{oi*}$ *for* $i = NR, N, R, O$.

Proof. According to Q_n^{ni*}, Q_r^{ni*}, Q_n^{oi*} and Q_r^{oi*} $(i = NR, N, R, O)$, we have

Condition	$(1-\delta_r)(s+v) \ge (1-\delta_o)c_r - (\delta_r - \delta_o)c_n$
$c_r \le \delta_r c_n$	$Q_N^{NR*} = \frac{1}{2} - \frac{c_n - c_r}{2(1-\delta_r)}$ $Q_R^{NR*} = \frac{\delta_r(\delta_r - \delta_o)c_n - [(1-\delta_o)\delta_r - \alpha(1-\delta_r)\delta_o]c_r}{2\delta_r(1-\delta_r)(\delta_r - \delta_o)} + \frac{(1-\alpha)(s+v)}{2(\delta_r - \delta_o)}$
$c_r > \delta_r c_n$	$Q_N^{R*} = \frac{1}{2} - \frac{(1-\alpha\delta_r)c_n - (1-\alpha)c_r}{2(1-\delta_r)}$ $Q_R^{R*} = (1-\alpha)\frac{(\delta_r - \delta_o)c_n - (1-\delta_o)c_r + (1-\delta_r)(s+v)}{2(1-\delta_r)(\delta_r - \delta_o)}$
	$(1-\delta_r)(s+v) < (1-\delta_o)c_r - (\delta_r - \delta_o)c_n$
$c_r \le \delta_r c_n$	$Q_N^{N*} = \frac{1}{2} - \frac{[(1-\delta_r) + \alpha(\delta_r - \delta_o)]c_n - \alpha(1-\delta_o)c_r}{2(1-\delta_r)(1-\delta_o)} + \frac{(1-\alpha)(s+v)}{2(1-\delta_o)}$ $Q_R^{N*} = \alpha\frac{\delta_r c_n - c_r}{2\delta_r(1-\delta_r)}$
$c_r < \delta_r c_n$	$Q_N^{O*} = \frac{1}{2} - \frac{(1-\alpha\delta_o)c_n - (1-\alpha)(s+v)}{2(1-\delta_o)}$ $Q_R^{O*} = 0$

When $c_r \le \delta_r c_n$, we have

$$\frac{\partial Q_N^{NR*}}{\partial s} = 0, \quad \frac{\partial Q_R^{NR*}}{\partial s} = \frac{1-\alpha}{2(\delta_r - \delta_o)} > 0,$$

for $(1-\delta_r)(s+v) \ge (1-\delta_o)c_r - (\delta_r - \delta_o)c_n$, and

$$\frac{\partial Q_N^{N*}}{\partial s} = \frac{1-\alpha}{2(1-\delta_o)} > 0, \quad \frac{\partial Q_R^{N*}}{\partial s} = 0,$$

for $(1-\delta_r)(s+v) < (1-\delta_o)c_r - (\delta_r - \delta_o)c_n$. Analogously, it is easy to see that when $c_r > \delta_r c_n$,

$$\frac{\partial Q_N^{R*}}{\partial s} = 0, \quad \frac{\partial Q_R^{R*}}{\partial s} = \frac{1-\alpha}{2(\delta_r - \delta_o)} > 0,$$

for $(1-\delta_r)(s+v) \ge (1-\delta_o)c_r - (\delta_r - \delta_o)c_n$, and

$$\frac{\partial Q_N^{N*}}{\partial s} = \frac{1-\alpha}{2(1-\delta_o)} > 0, \quad \frac{\partial Q_R^{N*}}{\partial s} = 0,$$

for $(1-\delta_r)(s+v) < (1-\delta_o)c_r - (\delta_r - \delta_o)c_n$. □

Although the optimal prices of the two types of products are independent on the subsidy of the government, the subsidy directly affects the demands from trade-in consumers and therefore affects the production decisions in the different market scenarios. Corollary 1 indicates this insight by revealing the changes of demands for the new products and the remanufactured products under the different market scenarios.[2] According to this corollary, the firm who has cost advantage in remanufacturing ($c_r \le \delta_r c_n$) produces more remanufactured products and less new products under a high subsidy scheme (i.e., $(1-\delta_r)(s+v) \ge (1-\delta_o)c_r - (\delta_r - \delta_o)c_n$). When the subsidy is not appealing to customers ($(1-\delta_r)(s+v) < (1-\delta_o)c_r - (\delta_r - \delta_o)c_n$), the manufacturer will reduce the production of the remanufactured products and optimize its profits by producing more new products. Similarly, for the firm who has cost disadvantage in remanufacturing ($c_r > \delta_r c_n$), it also increases the production of the remanufactured products under the high subsidy scheme and produces less under the low subsidy scheme. In particular, the manufacturer does not remanufacture under a high remanufacturing cost and a low subsidy. Therefore, the subsidy schemes of the government cannot only stimulate the trade-in of customers, but might also be able to facilitate the supply of remanufactured products, which in turn can mitigate the environmental damage of dated products.

These results for the benchmark model will be compared with those under carbon regulations to reveal the impacts of different

[2] Note that the demands for the new and the remanufactured products are obtained under different conditions corresponding to different market scenarios; we nevertheless can compare the overall demands under different scenarios.

emission constraints on the manufacturer's decisions in the subsequent sections.

4. Models under carbon regulations

4.1. Model formulation

To limit carbon emissions, carbon regulations are usually implemented by imposing emissions costs on the firms. Let the costs associated with the emissions be $C_E(Q_N, Q_R)$, where Q_N and Q_R are the demands of new products and remanufactured products generated from new market and replacement market, respectively, i.e., $Q_N = Q_n^n + Q_n^o$, $Q_R = Q_r^n + Q_r^o$. The decisions of the manufacturer can then be described as a nonlinear optimization problem.

$$\max \quad \pi_T(p_n, p_r, p_o)$$
$$= (p_n - c_n)\left(Q_n^n + Q_n^o\right) + (p_r - c_r)\left(Q_r^n + Q_r^o\right) - (p_o - v)\left(Q_n^o + Q_r^o\right) - C_E(Q_N, Q_R)$$
$$\text{s.t.} \quad \begin{cases} Q_n^n \ge 0 \\ Q_n^o \ge 0 \\ Q_r^n \ge 0 \\ Q_r^o \ge 0 \end{cases}$$

Here $C_E(\cdot)$ is increasing in Q_N and Q_R. In other words, when more new/remanufactured products are produced, more emissions costs are incurred. It provides a general denotation for capturing the influences of carbon regulations on the manufacturer's profits. Actually it can be expressed explicitly, given a specific regulation. Next, we discuss two commonly adopted regulations—carbon tax and cap and trade.

Under the carbon tax policy, a tax is imposed for carbon emissions. Like the tax in British Columbia in Canada, a broadly based carbon tax on the purchase and use of fossil fuels, such as gasoline, heating fuel and coal, is imposed by the government. Accordingly, we define the carbon tax imposed on the manufacturer as the additional linear cost associated with the carbon emissions. In general, remanufactured products are associated with less carbon emissions than new products due to the energy and material savings. We assume that the carbon emissions of producing a new product is e_n ($e_n \ge 0$) and that of producing a remanufactured product is e_r ($e_r \ge 0$), where $e_n > e_r$ means that remanufactured products are more environmentally friendly. Therefore, the carbon emission cost of the manufacturer for a new product (a remanufactured product) can be denoted as $e_n t$ ($e_r t$), where t represents the rate of carbon tax levied by the government. Then $C_E(\cdot)$ can be expressed as $C_E(Q_N, Q_R) = (e_n Q_N + e_r Q_R)t$.

On the other hand, under the cap and trade system, firms are subject to carbon caps imposed primarily by the government. If manufacturer's emissions exceed the cap, additional emission permits must be purchased from the emission trading market; contrarily, the manufacturer can get extra profits from selling the excess permits to other emission demanders if its emissions are less than its cap. Therefore, the price of the permits is determined by the number of available permits and the demand for them in the market. Following the notation in the case of carbon tax policy, we denote e_n ($e_n \ge 0$) as the carbon emissions of producing a unit of new products and e_r ($e_n > e_r \ge 0$) as the carbon emissions of producing a unit of remanufactured products. The cap imposed by the government is denoted as C, and the price of the unit emissions permit is p_e. Thus, emission costs under the cap and trade can be expressed as $C_E(Q_N, Q_R) = (e_n Q_N + e_r Q_R - C)p_e$.

The linear cost structures for carbon emissions are commonly adopted in the literature (see, for example, [3,4], and [6]). Some complicated policies are also considered in the literature (see, for example, [18] and [19]). However, due to the difficulties in implementation of more complicated policies, linear regulations are often used in practice. Examples include the carbon tax of Europe, Canada, and some regions in China, where an extra cost in unit energy consumption is incurred to limit carbon emissions. Thus in this paper we consider two commonly used carbon emissions regulations with a linear cost structure.

4.2. The optimal solutions

As analyzed in the base model, demands are from the new market and the replacement market, which depend on the pricing policies for new and remanufactured products. According to the demand functions in Table 1, we obtain the optimal pricing policies under the carbon tax by Proposition 1, as depicted in the following corollary.

Corollary 2. *Under the carbon regulations, the optimal pricing policies of the manufacturer are*

(i) *When* $(e_r - \delta_r e_n)k \le \delta_r c_n - c_r$ *and* $(1-\delta_r)(v+s) \ge (1-\delta_o)(c_r + e_r k) - (\delta_r - \delta_o)(c_n + e_n k)$, *the remanufactured products are supplied in both the new market and the replacement market. The manufacturer's pricing policy is* $p_n^{**} = (1 + c_n + e_n k)/2$, $p_r^{**} = (\delta_r + c_r + e_r k)/2$ *and* $p_o^{**} = (\delta_o + v - s)/2$.

(ii) *When* $(e_r - \delta_r e_n)k > \delta_r c_n - c_r$ *and* $(1-\delta_r)(v+s) \ge (1-\delta_o)(c_r + e_r k) - (\delta_r - \delta_o)(c_n + e_n k)$, *the remanufactured products are supplied only in the replacement market; while if* $(e_r - \delta_r e_n)k \le \delta_r c_n - c_r$ *and* $(1-\delta_r)(v+s) < (1-\delta_o)(c_r + e_r k) - (\delta_r - \delta_o)(c_n + e_n k)$, *they are supplied only in the new market. In both of these two scenarios, the pricing policy of the manufacturer is* $p_n^{**} = (1 + c_n + e_n k)/2$, $p_r^{**} = (\delta_r + c_r + e_r k)/2$ *and* $p_o^{**} = (\delta_o + v - s)/2$.

(iii) *When* $(e_r - \delta_r e_n)k > \delta_r c_n - c_r$ *and* $(1-\delta_r)(v+s) < (1-\delta_o)(c_r + e_r k) - (\delta_r - \delta_o)(c_n + e_n k)$, *the remanufactured products are neither supplied in the new market nor in the replacement market. The pricing policy of this case is* $p_n^{**} = (1 + c_n + e_n k)/2$ *and* $p_o^{**} = (\delta_o + v - s)/2$.

Here k is the tax rate t under the carbon tax policy and the permit price p_e *under the cap and trade regulation.*

Technically, Corollary 2 is implied by Proposition 1 and therefore it possesses similar structures. However, Corollary 2 helps us better understand the production strategies in the presence of carbon regulations. It points out that under carbon regulations the carbon emission efficiencies of the firm (e_r,e_n) have great impacts on its optimal production strategies. For example, according to Proposition 1, when $\delta_r c_n \ge c_r$ and $(\delta_r - \delta_o)c_n - (1-\delta_o)c_r + (1-\delta_r)(v+s) \ge 0$, it is optimal to sell the remanufactured product at the price $p_r^* = (\delta_r + c_r)/2$. However, Corollary 2 shows that even if these two conditions are satisfied, the remanufactured products are not supplied as long as e_r and e_n satisfy $(e_r - \delta_r e_n)k \ge \delta_r c_n - c_r$ and $[(1-\delta_o)e_r - (\delta_r - \delta_o)e_n]k > (\delta_r - \delta_o)c_n - (1-\delta_o)c_r + (1-\delta_r)(v+s)$. According to the past literature, the firm's remanufacturing is mainly driven by its cost efficiency. This corollary, however, indicates that *emission efficiencies are also important factors in determining production strategies when carbon regulations are introduced.*

Corollary 2 also shows that the optimal solutions under both carbon tax and cap and trade regulations have a similar structure. In fact, both of these two regulations are based on cost incentives to limit the carbon emissions. The former is regulated by the government through imposing a tax for each unit of emissions, while the latter depends on market regulation through the price of emission permits. Therefore, we take the solutions under carbon tax policy for illustration in the rest of this subsection.[3] We will an-

[3] In fact, the solutions under the carbon tax are quite analogous to those under the cap and trade policy when the tax rate t is replaced by the permits price p_e.

Table 2
Demands of new products and remanufactured products under different conditions when carbon regulations are introduced.

Condition	$(1-\delta_r)(v+s) \geq (1-\delta_o)(c_r+e_rt)-(\delta_r-\delta_o)(c_n+e_nt)$	$(1-\delta_r)(v+s) < (1-\delta_o)(c_r+e_rt)-(\delta_r-\delta_o)(c_n+e_nt)$
$(e_r-\delta_re_n)t \leq \delta_rc_n-c_r$	$Q_n^{nNR**}=\frac{\alpha}{2}\left[1-\frac{(c_n+e_nt)-(c_r+e_rt)}{1-\delta_r}\right]$	$Q_n^{nN**}=\frac{\alpha}{2}\left[1-\frac{(c_n+e_nt)-(c_r+e_rt)}{1-\delta_r}\right]$
	$Q_r^{nNR**}=\frac{\alpha[\delta_r(c_n+e_nt)-(c_r+e_rt)]}{2\delta_r(1-\delta_r)}$	$Q_r^{nN**}=\frac{\alpha[\delta_r(c_n+e_nt)-(c_r+e_rt)]}{2\delta_r(1-\delta_r)}$
	$Q_n^{oNR**}=\frac{(1-\alpha)}{2}\left[1-\frac{(c_n+e_nt)-(c_r+e_rt)}{1-\delta_r}\right]$	$Q_n^{oN**}=\frac{(1-\alpha)}{2}\left(1-\frac{c_n+e_nt}{1-\delta_0}\right)+\frac{(1-\alpha)(v+s)}{2(1-\delta_o)}$
	$Q_r^{oNR**}=\frac{(1-\alpha)[(\delta_r-\delta_o)(c_n+e_nt)-(1-\delta_o)(c_r+e_rt)]}{2(\delta_r-\delta_o)(1-\delta_r)}+\frac{(1-\alpha)(v+s)}{2(\delta_r-\delta_o)}$	$Q_r^{oN**}=0$
$(e_r-\delta_re_n)t > \delta_rc_n-c_r$	$Q_n^{nR**}=\frac{\alpha(1-c_n-e_nt)}{2}$	$Q_n^{nO**}=\frac{\alpha(1-c_n-e_nt)}{2}$
	$Q_r^{nR**}=0$	$Q_r^{nO**}=0$
	$Q_n^{oR**}=\frac{(1-\alpha)}{2}[1-\frac{(c_n+e_nt)-(c_r+e_rt)}{1-\delta_r}]$	$Q_n^{oO**}=\frac{(1-\alpha)}{2}\left(1-\frac{c_n+e_nt}{1-\delta_0}\right)+\frac{(1-\alpha)(v+s)}{2(1-\delta_o)}$
	$Q_r^{oR**}=\frac{(1-\alpha)[(\delta_r-\delta_o)(c_n+e_nt)-(1-\delta_o)(c_r+e_rt)]}{2(\delta_r-\delta_o)(1-\delta_r)}+\frac{(1-\alpha)(v+s)}{2(\delta_r-\delta_o)}$	$Q_r^{oO**}=0$

alyze their differences on influencing the firm's profits in the next subsection.

Different from the case of not considering carbon regulations, under the carbon tax policy, the manufacturer's price decisions mainly depend on the tax rate and trade-in subsidies determined by the government. As stated in Corollary 2, the manufacturer is willing to provide remanufactured products for the new market only when the tax rate t satisfies $(e_r-\delta_re_n)t \leq \delta_rc_n - c_r$. Under this condition, the availability of remanufactured products in the replacement market is also motivated by the high trade-in subsidy because $(1-\delta_r)(v+s) \geq (1-\delta_o)(c_r+e_rt)-(\delta_r-\delta_o)(c_n+e_nt)$. When $(e_r-\delta_re_n)t > \delta_rc_n-c_r$, however, the manufacturer would have no incentive to provide remanufactured products for the new market—even under the high trade-in subsidy, the remanufactured products are only available in the replacement market. Therefore, the introduction of the tax policy may have a significant impact on the production policies of the new market. It has relatively less influence in the replacement market due to the offset by the subsidy policy for trade-ins.

Corollary 3. *In each of the four market scenarios under the carbon regulations, we have*

(i) $\partial p_n^{**}/\partial t > 0$, $\partial p_r^{**}/\partial t > 0$ *and* $\partial p_o^{**}/\partial t = 0$;

(ii) $\partial p_n^{**}/\partial t > \partial p_r^{**}/\partial t$.

Proof. According to the optimal price strategies of the firm, we have

$$\frac{\partial p_n^{**}}{\partial t}=\frac{e_n}{2}>0,\quad \frac{\partial p_r^{**}}{\partial t}=\frac{e_r}{2}>0,\quad \frac{\partial p_o^{**}}{\partial t}=0.$$

Also, since $e_n > e_r$, we have

$$\frac{\partial p_n^{**}}{\partial t}>\frac{\partial p_r^{**}}{\partial t}.$$

The proof is complete. □

The optimal prices of new products and remanufactured products have analogous solution structures in different scenarios, which are similar to the results of the base model. However, compared with the base model, the introduction of the carbon tax increases the price of both new and remanufactured products without any change in trade-in rebate. As Corollary 3 shows, the prices of both new and remanufactured products are increasing in the tax rate t, while the trade-in rebate is not affected by the tax. Intuitively, additional costs are imposed on the process of production to limit the production quantity, but the recycle process of the firm is not influenced. That is, customers may suffer from carbon regulations due to the extra costs shifting from the manufacturer to them. Moreover from this corollary, we see that the tax policy may have more significant impacts on the prices of new products than remanufactured products due to the difference of emissions between these two types of products.

Under the carbon tax policy, the demands of new products and remanufactured products for scenario NR, scenario N, scenario R and scenario O[4] can be described in the following table in a manner similar to Proposition 2.

Tax policy may have different impacts on the manufacturer's decisions, depending on its characteristics regarding production and emission efficiencies. The results are illustrated in the following corollary, which can be obtained easily from Table 2.

Corollary 4. (i) *If* $c_r \leq \delta_rc_n$ *and* $e_r \leq \delta_re_n$, *the manufacturer always provides the remanufactured products for the new market for any* $t \geq 0$;

(ii) *if* $c_r \leq \delta_rc_n$ *and* $e_r > \delta_re_n$, *the manufacturer provides the remanufactured products for the new market only if* $t \leq \frac{\delta_rc_n-c_r}{e_r-\delta_re_n}$;

(iii) *if* $c_r > \delta_rc_n$ *and* $e_r < \delta_re_n$, *the manufacturer provides the remanufactured products for the new market only if* $t \geq \frac{\delta_rc_n-c_r}{e_r-\delta_re_n}$;

(iv) *if* $c_r > \delta_rc_n$ *and* $e_r \geq \delta_re_n$, *the manufacturer does not provide the remanufactured products for the new market for any* $t \geq 0$.

Because the implementation of the carbon tax affects the availability of remanufactured products in the new market, the firm may encounter different influences depending on the advantages in remanufacturing cost or remanufacturing emissions. For the manufacturer who has the cost advantage ($c_r \leq \delta_rc_n$), its remanufacturing strategy for the new market is independent of the tax policy if it also has an advantage in emissions ($e_r \leq \delta_re_n$). But it

[4] Similar to the earlier classification, scenario NR, scenario N, scenario R, and scenario O denote different market situations. For example, scenario NR represents the situation in which the firm provides both the new and the remanufactured products for consumers. Obviously, under different regulations, the conditions that distinguish these market scenarios may be different. For instance, under carbon regulation, these conditions depend on the tax rate, while they have nothing to do with tax when the tax is absent.

would be willing to provide the remanufactured products in the new market only under a low tax rate, i.e., $t \le (\delta_r c_n - c_r)/(e_r - \delta_r e_n)$, once it loses its advantage in emissions ($e_r > \delta_r e_n$). Interestingly, for the firm who does not have an advantage in remanufacturing costs ($c_r > \delta_r c_n$) but does have an advantage in emissions ($e_r < \delta_r e_n$), it has an incentive to produce the remanufactured products for the new market only under a *high* tax rate, i.e., $t \ge (\delta_r c_n - c_r)/(e_r - \delta_r e_n)$. However, when it has neither the cost advantage nor the emissions advantage, it is optimal to never produce the remanufactured products for the new market. In fact, the emissions advantage can be valuable only for a high tax rate when the manufacturer has the disadvantage in remanufacturing cost because the emissions cost savings associated with the emissions advantage can offset the disadvantage of remanufacturing cost under a high tax rate. Once the manufacturer loses this emissions advantage, it cannot benefit from remanufacturing any more and, therefore, does not provide remanufactured products for the new market. In contrast to the situations where carbon regulations are absent (as stated in Corollary 1), this indicates that the introduction of carbon regulations provides a new opportunity for the firm who does not have remanufacturing cost advantage but does have emission advantage to gain competitive advantages from remanufacturing. That is, *the carbon regulations of the government change the firm's competitive advantages; the regulations generally hurt the firm's profit but at the same time provide some flexibilities for the firm to improve its profitability*.

Define the total demand of the new products in the new market and the replacement market as Q_N^{i**} and the total demand of the remanufactured products in the new market and the replacement market as Q_R^{i**} for $i = NR, N, R, O$, where $Q_N^{i**} = Q_n^{ni**} + Q_n^{oi**}$ and $Q_R^{i**} = Q_r^{ni**} + Q_r^{oi**}$. We can derive the following corollary.

Corollary 5. *In the four scenarios under the carbon tax policy, we have*

(i) *for scenario NR,* $\partial Q_N^{NR**}/\partial t < 0$, $\partial Q_R^{NR**}/\partial t \ge 0$ *if* $\delta_r(\delta_r - \delta_o)e_n - [(1-\delta_o)\delta_r - \alpha(1-\delta_r)\delta_o]e_r \ge 0$, $\partial Q_R^{NR**}/\partial t < 0$ *otherwise*;

(ii) *for scenario N,* $\partial Q_N^{N**}/\partial t < 0$, $\partial Q_R^{N**}/\partial t \ge 0$ *if* $\delta_r e_n \ge e_r$, $\partial Q_R^{N**}/\partial t < 0$ *otherwise*;

(iii) *for scenario R,* $\partial Q_N^{R**}/\partial t < 0$, $\partial Q_R^{R**}/\partial t \ge 0$ *if* $(\delta_r - \delta_o)e_n \ge (1-\delta_o)e_r$, $\partial Q_R^{R**}/\partial t < 0$ *otherwise*;

(iv) *for scenario O,* $\partial Q_N^{O**}/\partial t < 0$ *and* $\partial Q_R^{O**}/\partial t = 0$.

Proof. As stated before, we can calculate Q_N^{**} and Q_R^{**} in different scenarios as follows.

Condition	$(1-\delta_r)(s+v) \ge (1-\delta_o)(c_r+e_r t) - (\delta_r-\delta_o)(c_n+e_n t)$
$(e_r - \delta_r e_n)t \le \delta_r c_n - c_r$	$Q_N^{NR*} = \frac{1}{2} - \frac{(c_n+e_n t)-(c_r+e_r t)}{2(1-\delta_r)}$
	$Q_R^{NR*} = \frac{\delta_r(\delta_r-\delta_o)(c_n+e_n t) - [(1-\delta_o)\delta_r - \alpha(1-\delta_r)\delta_o](c_r+e_r t)}{2\delta_r(1-\delta_r)(\delta_r-\delta_o)} + \frac{(1-\alpha)(s+v)}{2(\delta_r-\delta_o)}$
$(e_r - \delta_r e_n)t > \delta_r c_n - c_r$	$Q_N^{R*} = \frac{1}{2} - \frac{(1-\alpha\delta_r)(c_n+e_n t) - (1-\alpha)(c_r+e_r t)}{2(1-\delta_r)}$
	$Q_R^{R*} = (1-\alpha)\frac{(\delta_r-\delta_o)(c_n+e_n t) - (1-\delta_o)(c_r+e_r t) + (1-\delta_r)(s+v)}{2(1-\delta_r)(\delta_r-\delta_o)}$
	$(1-\delta_r)(s+v) < (1-\delta_o)(c_r+e_r t) - (\delta_r-\delta_o)(c_n+e_n t)$
$(e_r - \delta_r e_n)t \le \delta_r c_n - c_r$	$Q_N^{N*} = \frac{1}{2} - \frac{[(1-\delta_r)+\alpha(\delta_r-\delta_o)](c_n+e_n t) - \alpha(1-\delta_o)(c_r+e_r t)}{2(1-\delta_r)(1-\delta_o)} + \frac{(1-\alpha)(s+v)}{2(1-\delta_o)}$
	$Q_R^{N*} = \alpha\frac{\delta_r(c_n+e_n t)-(c_r+e_r t)}{2\delta_r(1-\delta_r)}$
$(e_r - \delta_r e_n)t < \delta_r c_n - c_r$	$Q_N^{O*} = \frac{1}{2} - \frac{(1-\alpha\delta_o)(c_n+e_n t) - (1-\alpha)(s+v)}{2(1-\delta_o)}$
	$Q_R^{O*} = 0$

Therefore, in scenario NR, it is easy to prove that

$$\frac{\partial Q_N^{NR**}}{\partial t} = -\frac{e_n - e_r}{2(1-\delta_r)} < 0,$$

$$\frac{\partial Q_R^{NR**}}{\partial t} = \frac{\delta_r(\delta_r-\delta_o)e_n - [(1-\delta_o)\delta_r - \alpha(1-\delta_r)\delta_o]e_r}{2\delta_r(\delta_r-\delta_o)(1-\delta_r)}.$$

So we have $\partial Q_R^{NR**}/\partial t \ge 0$ when $\delta_r(\delta_r-\delta_o)e_n - [(1-\delta_o)\delta_r - \alpha(1-\delta_r)\delta_o]e_r \ge 0$ and $\partial Q_R^{NR**}/\partial t < 0$ otherwise.

Similarly, we can prove $\partial Q_N^{i**}/\partial t$ for $i = N, R, O$. Also, we have $\partial Q_R^{N**}/\partial t \ge 0$ if $\delta_r e_n \ge e_r$, $\partial Q_R^{N**}/\partial t < 0$ otherwise for scenario N. For scenario R, if $(\delta_r - \delta_o)e_n \ge (1-\delta_o)e_r$, we can prove $\partial Q_R^{R**}/\partial t \ge 0$, otherwise, $\partial Q_R^{R**}/\partial t < 0$. Last, in scenario O, it is not hard to show $\partial Q_R^{O**}/\partial t = 0$ for any $t \ge 0$. □

With the introduction of the carbon tax policy, the demands in the two markets depend on the tax rate. As stated in Corollary 3, the new products suffer more from the tax than do the remanufactured products. In particular, according to Corollary 5, the demands of the new products are always decreasing in the tax rate t in all four scenarios. It indicates that the new products are less profitable and are limited inevitably due to the introduction of the carbon tax. As for the remanufactured products, the results depend on the emissions advantage of the manufacturer. In scenario NR, the demands of the remanufactured products may be increasing in the tax rate t when the emissions of the firm satisfy $\delta_r(\delta_r-\delta_o)e_n - [(1-\delta_o)\delta_r - \alpha(1-\delta_r)\delta_o]e_r \ge 0$. In scenario N and scenario R, analogous conditions can also be derived as shown in Corollary 5. However, in scenario O, the manufacturer does not produce the remanufactured products any more due to the low subsidy and the possibly inappropriate tax rate. In general, because of the emissions disadvantage of the new products relative to the remanufactured products ($e_n > e_r$), the manufacturer always chooses to produce more remanufactured products to lessen the negative effects caused by the tax policy. However, the firm would also produce less remanufactured products when its emissions advantage is not dominant, as in scenario NR where $\delta_r(\delta_r-\delta_o)e_n - [(1-\delta_o)\delta_r - \alpha(1-\delta_r)\delta_o]e_r < 0$.

The above results characterize the demands of new and remanufactured products. Accordingly, the influences of carbon regulations on the *new market* and the *replacement market* can also be illustrated as follows. Define the total production quantity of the new market as Q_{NM}^{i*} and the total production quantity of the replacement market as Q_{OM}^{i*} for $i = NR, N, R, O$, where $Q_{NM}^{i*} = Q_n^{ni**} + Q_r^{ni**}$ and $Q_{OM}^{i*} = Q_n^{oi**} + Q_r^{oi**}$.

Proposition 3. *Under the carbon tax policy, we have*

(i) $\partial Q_{NM}^{i*}/\partial t < 0$ *and* $\partial Q_{OM}^{i*}/\partial t < 0$ *in all four scenarios, where* $i = NR, N, R, O$;

(ii) *in scenario NR,* $|\partial Q_{NM}^{NR*}/\partial t| > |\partial Q_{OM}^{NR*}/\partial t|$ *if* $\delta_r/(2\delta_r - \delta_o) < \alpha < 1$ *and* $|\partial Q_{NM}^{NR*}/\partial t| \le |\partial Q_{OM}^{NR*}/\partial t|$ *otherwise*;

(iii) *in scenario N,* $|\partial Q_{NM}^{N*}/\partial t| > |\partial Q_{OM}^{N*}/\partial t|$ *if* $\delta_r e_n/(\delta_r e_n + (1-\delta_o)e_r) < \alpha < 1$ *and* $|\partial Q_{NM}^{N*}/\partial t| \le |\partial Q_{OM}^{N*}/\partial t|$ *otherwise*;

(iv) *in scenario R,* $|\partial Q_{NM}^{R*}/\partial t| > |\partial Q_{OM}^{R*}/\partial t|$ *if* $e_r/(e_r + (\delta_r - \delta_o)e_n) < \alpha < 1$ *and* $|\partial Q_{NM}^{R*}/\partial t| \le |\partial Q_{OM}^{R*}/\partial t|$ *otherwise*;

(v) *in scenario O,* $|\partial Q_{NM}^{O*}/\partial t| > |\partial Q_{OM}^{O*}/\partial t|$ *if* $1/(2-\delta_o) < \alpha < 1$ *and* $|\partial Q_{NM}^{O*}/\partial t| \le |\partial Q_{OM}^{O*}/\partial t|$ *otherwise.*

Proof. According to the quantities of the new products and the remanufactured products of the two markets in the four market scenarios, the total demands of the two markets can be calculated as follows.

$$Q_{NM}^{NR*} = \frac{\alpha}{2}\left(1 - \frac{c_r + e_r t}{\delta_r}\right) \qquad Q_{NM}^{N*} = \frac{\alpha}{2}\left(1 - \frac{c_r + e_r t}{\delta_r}\right)$$

$$Q_{OM}^{NR*} = \frac{(1-\alpha)}{2}\left(1 - \frac{c_r + e_r t - s - v}{\delta_r - \delta_o}\right) \qquad Q_{OM}^{N*} = \frac{(1-\alpha)}{2}\left(1 - \frac{c_n + e_n t - s - v}{1 - \delta_o}\right)$$

$$Q_{NM}^{R*} = \frac{\alpha}{2}(1 - c_n - e_n t) \qquad Q_{NM}^{O*} = \frac{\alpha}{2}(1 - c_n - e_n t)$$

$$Q_{OM}^{R*} = \frac{(1-\alpha)}{2}\left(1 - \frac{c_r + e_r t - s - v}{\delta_r - \delta_o}\right) \qquad Q_{OM}^{O*} = \frac{(1-\alpha)}{2}\left(1 - \frac{c_n + e_n t - s - v}{1 - \delta_o}\right)$$

It is easy to show that $\partial Q_{NM}^{i*}/\partial t < 0$ and $\partial Q_{OM}^{i*}/\partial t < 0$ for the four scenarios, where $i = NR, N, R, O$. On the other hand, for scenario NR, we have $|\partial Q_{NM}^{NR*}/\partial t| = \alpha e_r/(2\delta_r)$ and $|\partial Q_{OM}^{NR*}/\partial t| = (1-\alpha)e_r/(2(\delta_r - \delta_o))$. It is not hard to prove that $|\partial Q_{NM}^{NR*}/\partial t| - |\partial Q_{OM}^{NR*}/\partial t| > 0$ if $\delta_r/(2\delta_r - \delta_o) < \alpha < 1$, and $|\partial Q_{NM}^{NR*}/\partial t| \le |\partial Q_{OM}^{NR*}/\partial t|$ otherwise. For scenario N, we also have $|\partial Q_{NM}^{N*}/\partial t| = \alpha e_r/(2\delta_r)$ and $|\partial Q_{OM}^{N*}/\partial t| = (1-\alpha)e_n/(2(1-\delta_o))$. According to $|\partial Q_{NM}^{N*}/\partial t| - |\partial Q_{OM}^{N*}/\partial t| > 0$, we must have $\delta_r e_n/(\delta_r e_n + (1-\delta_o)e_r) < \alpha < 1$. So if this condition holds, we have $|\partial Q_{NM}^{N*}/\partial t| > |\partial Q_{OM}^{N*}/\partial t|$, otherwise, $|\partial Q_{NM}^{N*}/\partial t| \le |\partial Q_{OM}^{N*}/\partial t|$. Similarly, for scenario R and scenario O, $|\partial Q_{NM}^{R*}/\partial t| = \alpha e_n/2$, $|\partial Q_{OM}^{R*}/\partial t| = (1-\alpha)e_r/(2(\delta_r - \delta_o))$, $|\partial Q_{NM}^{O*}/\partial t| = \alpha e_n/2$ and $|\partial Q_{OM}^{O*}/\partial t| = (1-\alpha)e_n/(2(1-\delta_o))$. So we can derive that $|\partial Q_{NM}^{R*}/\partial t| > |\partial Q_{OM}^{R*}/\partial t|$ if $e_r/(e_r + (\delta_r - \delta_o)e_n) < \alpha < 1$ and $|\partial Q_{NM}^{O*}/\partial t| > |\partial Q_{OM}^{O*}/\partial t|$ if $1/(2-\delta_o) < \alpha < 1$. □

Would the introduction of the carbon tax policy would harm the sales in the new market and the replacement market? If so, would the new market and the replacement market bear different negative influences? This proposition provides the answers for these questions. As we can see, the total demands are indeed decreased by the carbon regulations in the new market as well as the replacement market, although the regulations may be able to boost production of remanufactured products. Clearly the carbon tax limits the production of new products. It can also increase the production of remanufactured products under certain conditions. However, the negative effects on the new products cannot be offset by the increased sales (if any) of the remanufactured products. Therefore, the total demands in the two markets are decreasing in the tax rate. Also, the demands of the two markets have different sensitivities on the tax rate, which depends on the composition of each market. This is intuitive because the new market will suffer more from the imposition of the carbon tax when there are more new consumers.

4.3. The profits of the manufacturer

Compared with the demands in the base model, the introduction of carbon regulations is to limit the production of the manufacturer and therefore reduce carbon emissions. As discussed, in the presence of carbon regulations, the demands depend on the tax rate t under the carbon tax policy or on the emission permit price p_e under the cap and trade system. In addition this study also takes the trade-in policy into consideration, where the regulator encourages consumers to purchase new products or remanufactured products with their old ones being returned by offering subsidies. In this context, the government may affect the profits of the manufacturer in two ways: limiting the firm's productions by increasing the tax rate or compensating the firm's loss by increasing the subsidy. In this section, we will focus on the influences of government decisions on the profits of the firm.

First, we examine the impacts of the carbon tax policy on the manufacturer's profit. Under the carbon tax, for any market scenario i ($i = NR, N, R, O$), the manufacturer's profit can be expressed as

$$\pi_T^{i*} = (p_n^{**} - c_n - e_n t)Q_N^{i**} + (p_r^{**} - c_r - e_r t)Q_R^{i**} - (p_o^{**} - v)Q_{OM}^{i*},$$

where $Q_N^{i**} = Q_n^{ni**} + Q_n^{oi**}$, $Q_R^{i**} = Q_r^{ni**} + Q_r^{oi**}$ and $Q_{OM}^{i*} = Q_n^{oi**} + Q_r^{oi**}$. When there is no carbon tax policy, the government can promote the replacement market by providing a subsidy scheme. With the subsidy of the government, the manufacturer can recycle used products and sell more new products or remanufactured products at a lower cost. However, with the limitation of carbon emissions, the firm suffers from additional costs associated with emissions. According to the previous analysis, the sales of the remanufactured products may be enhanced although the demands for the new products are generally reduced. The total profits of the firm depend on the revenues from both the new and the remanufactured products. Therefore, the ultimate impact of carbon tax on profits lies on the joint effect of the decreased sales of the new products and the increased sales of the remanufactured ones. The following proposition summarizes this result.

Proposition 4. *Under the carbon tax policy, we have*

(i) $\partial \pi_T^{i*}/\partial t < 0$ *for* $i = NR, N, R, O$;

(ii) *for scenario NR and scenario R,* $\partial \pi_T^{NR*}/\partial s > 0$ *and* $\partial \pi_T^{R*}/\partial s > 0$ *if* $s > c_r + e_r t - v - (\delta_r - \delta_o)$, *and* $\partial \pi_T^{NR*}/\partial s \le 0$ *and* $\partial \pi_T^{R*}/\partial s \le 0$ *otherwise*;

(iii) *for scenario N and scenario O,* $\partial \pi_T^{N*}/\partial s > 0$ *and* $\partial \pi_T^{O*}/\partial s > 0$ *if* $s > c_n + e_n t - v - (1 - \delta_o)$, *and* $\partial \pi_T^{N*}/\partial s \le 0$ *and* $\partial \pi_T^{O*}/\partial s \le 0$ *otherwise.*

Proof. The profit of the manufacturer is

$$\begin{aligned}
\pi_T^{i*} &= (p_n^{**} - c_n - e_n t)Q_N^{i**} + (p_r^{**} - c_r - e_r t)Q_R^{i**} - (p_o^{**} - v)Q_{OM}^{i*} \\
&= (p_n^{**} - c_n - e_n t)\left(Q_n^{ni**} + Q_n^{oi**}\right) + (p_r^{**} - c_r - e_r t)\left(Q_r^{ni**} + Q_r^{oi**}\right) \\
&\quad -(p_o^{**} - v)\left(Q_n^{oi**} + Q_r^{oi**}\right) \\
&= (p_n^{**} - c_n - e_n t)Q_n^{ni**} + (p_r^{**} - c_r - e_r t)Q_r^{ni**} \\
&\quad + (p_n^{**} - c_n - e_n t - p_o^{**} + v)Q_n^{oi**} + (p_r^{**} - c_r - e_r t - p_o^{**} + v) \\
&\quad Q_r^{oi**} = (p_r^{**} - c_r - e_r t)\left(Q_n^{ni**} + Q_n^{ni**}\right) \\
&\quad + [(p_n^{**} - c_n - e_n t) - (p_r^{**} - c_r - e_r t)]\left(Q_n^{ni**} + Q_n^{oi**}\right) \\
&\quad + (p_r^{**} - c_r - e_r t - p_o^{**} + v)\left(Q_n^{oi**} + Q_r^{oi**}\right) \\
&= (p_r^{**} - c_r - e_r t)Q_{NM}^{i*} + (p_r^{**} - c_r - e_r t - p_o^{**} + v)Q_{OM}^{i*} \\
&\quad + [(p_n^{**} - c_n - e_n t) - (p_r^{**} - c_r - e_r t)]Q_N^{i*}.
\end{aligned}$$

It is easy to prove that $p_r^{**} - c_r - e_r t$, $p_r^{**} - c_r - e_r t - p_o^{**} + v$ and $(p_n^{**} - c_n - e_n t) - (p_r^{**} - c_r - e_r t)$ is decreasing in t. Also, according to Corollary 5 and Proposition 3, Q_{NM}^{i*}, Q_{OM}^{i*} and Q_N^{i*} decrease in t. So π_T^{i*} decreases in t, i.e., $\partial \pi_T^{i*}/\partial t < 0$ for $i = NR, N, R, O$.

In scenario NR, substituting the optimal price of products and demands into π_T^{i*}, we have

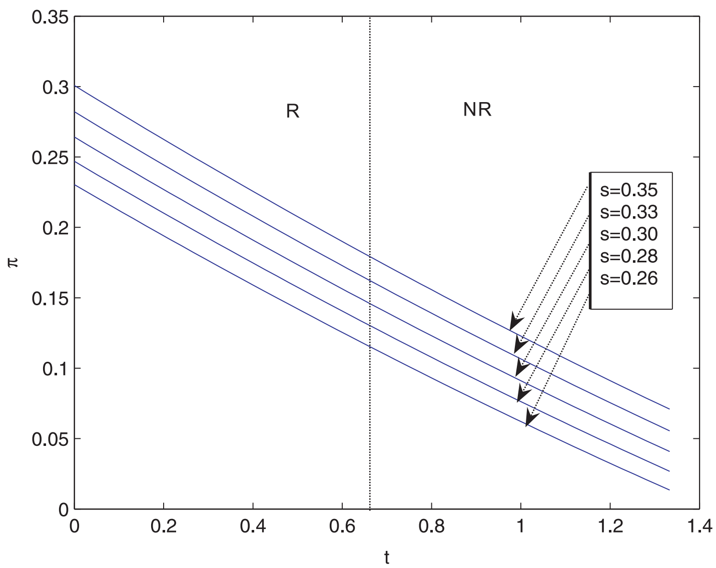
$$\frac{\partial \pi_T^{I*}}{\partial s} = \frac{1-\alpha}{4}\left[\frac{\delta_r - c_r - e_r t}{\delta_r - \delta_o} - \frac{\delta_o - v - s}{\delta_r - \delta_o} + 1 - \frac{c_r + e_r t - v - s}{\delta_r - \delta_o}\right],$$

If $s > c_r + e_r t - v - (\delta_r - \delta_o)$ we have $\partial\pi_T^{NR*}/\partial s > 0$. Otherwise, $\partial\pi_T^{NR*}/\partial s \le 0$. For scenario R, we also can have the same results. Similarly, in scenario N, substituting the optimal price of products and demands, we have

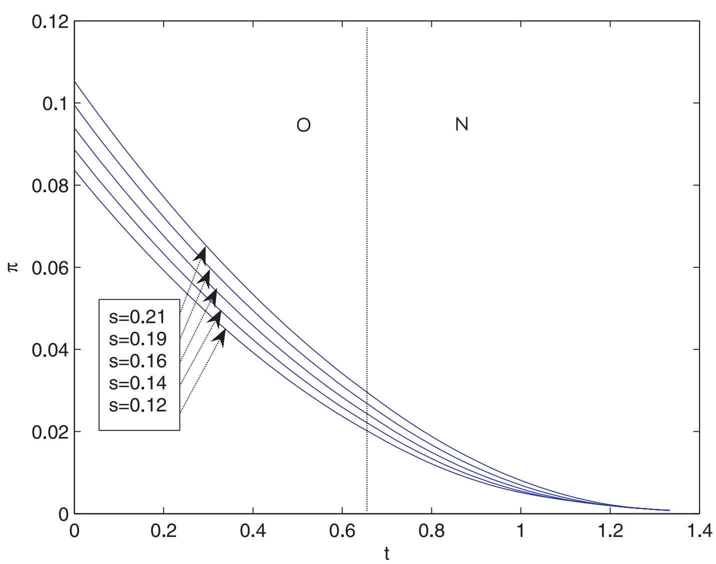
$$\frac{\partial\pi_T^{N*}}{\partial s} = \frac{1-\alpha}{4}\left[\frac{1-c_n-e_n t}{1-\delta_o} - \frac{\delta_o - v - s}{1-\delta_o} + 1 - \frac{c_n + e_n t - v - s}{1-\delta_o}\right].$$

So, if $s > c_n + e_n t - v - (1-\delta_o)$, we have $\partial\pi_T^{N*}/\partial s > 0$. If $s \le c_n + e_n t - v - (1-\delta_o)$, we have $\partial\pi_T^{N*}/\partial s \le 0$. The same results can be obtained for scenario O. □

Proposition 4 shows that with the introduction of the carbon tax, the profit loss due to the decreased demands of the new products overweighs the benefit of increased demands of the remanufactured products, and consequently the profits of the manufacturer decrease in the tax rate. It means that the carbon tax imposed by the government inevitably hurts the interest of the firm, although it can make contributions in improving the sales of remanufactured products. Indeed, this result is consistent with our intuition because the imposed tax makes the firm suffer from additional emissions costs. However, under the trade-in policy, the firm's profits are increasing in the subsidy s under certain conditions depending on the production and emissions costs of the new and the remanufactured products as well as the customers' valuation on products. In particular, in scenario NR and scenario R where $(1-\delta_r)(v+s) \ge (1-\delta_o)(c_r+e_r t) - (\delta_r - \delta_o)(c_n + e_n t)$, the threshold of the subsidy is $c_r + e_r t - v - (\delta_r - \delta_o)$, which reflects the characteristics of the remanufactured products. While in scenario N and scenario O where $(1-\delta_r)(v+s) < (1-\delta_o)(c_r+e_r t) - (\delta_r - \delta_o)(c_n + e_n t)$, the threshold of s becomes $c_n + e_n t - v - (1-\delta_o)$, which reflects the characteristics of the new products. Apparently the subsidy can promote the products of the replacement



(a) scenario NR and scenario R



(b) scenario N and scenario O

Fig. 1. The manufacturer's profit π with respect to the carbon tax rate t and the subsidy s in four scenarios, where c_n=0.4, c_r=0.3, e_n=0.4, e_r=0.25, $\delta_r = 0.7$, $\delta_o = 0.5$, v=0.2, $\alpha = 0.5$.

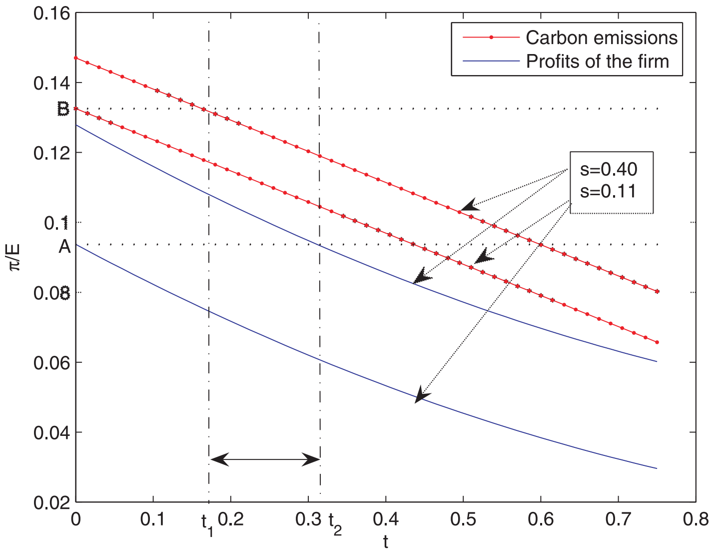


Fig. 2. The profits π and carbon emissions E of the manufacturer with respect to the tax rate t, where c_n=0.4, c_r=0.25, e_n=0.4, e_r=0.2, $\delta_r = 0.7$, $\delta_o = 0.5$, v=0.1, $\alpha = 0.9$. These settings reflect the situations of scenario NR.

market, including the new products and the remanufactured products. In scenario NR and scenario R where there is a high subsidy offered by the government, the firm is willing to provide the remanufactured products for the replacement market. So the government can compensate the firm via the promotion of remanufactured products. Nevertheless, in scenario N and scenario O where the subsidy is low, the government may consider changing the subsidy to promote the new product demands since there are no remanufactured products in the replacement market in these two scenarios.

Fig. 1 further illustrates Proposition 4 numerically. The graphs are based on the situations where the firm has the emissions advantage but lacks the remanufacturing cost advantage (i.e., $e_r < \delta_r e_n$ and $\delta_r c_n < c_r$). Therefore, in Fig. 1(a), the right area denotes scenario NR and the left area denotes scenario R, while the right area of Fig. 1(b) represents scenario N and the left area represents scenario O. For all four scenarios, the manufacturer's total profit decreases in the carbon tax and increases in the subsidy.

However, in these scenarios new products or remanufactured products are also increased with the increase of the subsidy s, which indicates possible increase in the total emissions. Recall that the introduction of the carbon regulations is to limit the carbon emissions of the firm. It may be problematic that the government has the incentive to improve the subsidy to compensate for the firm's loss caused by emissions limitation. Obviously if the improvement of the subsidy also increases the total emissions, this improvement may be unfavorable for the government although it is beneficial for the firm. We provide a numerical example to illustrate this. In Fig. 2, two cases about carbon emissions and profits are presented: s=0.11, s=0.40. The profits curve and emissions curve depict the changes of the firm's profits and carbon emissions with the raise of the tax rate. When $s = 0.11$, point A represents the profits level when the tax is absent (i.e., t=0). Similarly, point B represents the emissions level when t=0. We see that both the firm's profits and carbon emissions are reduced with the introduction of the tax. Furthermore, when the subsidy is improved (i.e., s=0.4), the firm enjoys more profits but also produces more emissions. However, according to Fig. 2, the benefits associated with the subsidy improvement (profits increase) overweigh the negative effects caused by it (emissions increase). In particular, if the carbon tax rate t is greater than t_1 and less than t_2, the profits of the manufacturer are more while the total emissions are less than the case where the tax is absent. Here, t_1 and t_2 denote the thresholds of the tax rate in a well-designed carbon tax. In fact, though the carbon tax would add costs of the manufacturer, the subsidy can improve the firm's profits. Whether or not the manufacturer can benefit from the carbon tax may depend on the tradeoff between these two opposite effects. This figure just presents a possibility for us that an efficient subsidy scheme can eliminate the negative effects caused by the carbon tax when this regulation is well designed, that is, when the tax rate satisfies $t_1 \le t \le t_2$. This indicates that the government indeed has the motivation to implement the subsidy scheme to compensate the firm. Also, with well-designed tax policies, the subsidy scheme can also increase the profits of the firm without increasing carbon emissions.

We now move on to the analysis in the context of the cap and trade system. Under cap and trade regulation, the manufacturer's profit can be expressed as

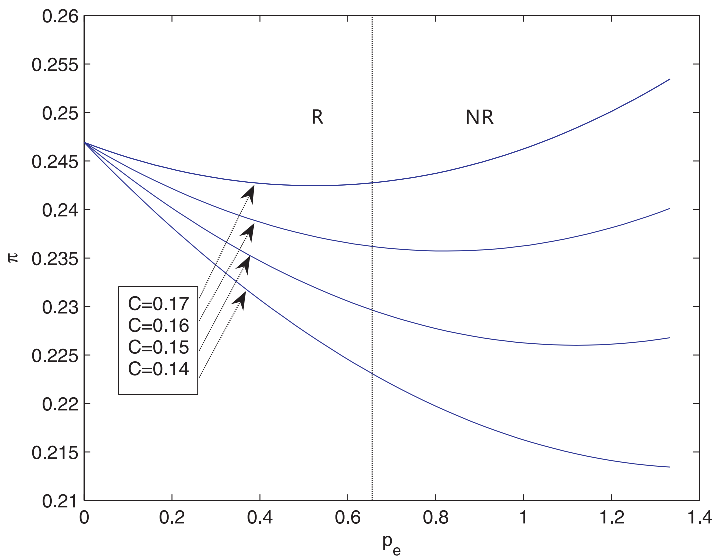
$$\begin{aligned}\pi_C^{i*} &= (p_n^{**} - c_n)Q_N^{i**} + (p_r^{**} - c_r)Q_R^{i**} - (p_o^{**} - v)Q_{OM}^{i*} \\ &\quad - p_e\left[e_n Q_N^{i**} + e_r Q_R^{i**} - C\right] \\ &= (p_n^{**} - c_n - e_n p_e)Q_N^{i**} + (p_r^{**} - c_r - e_r p_e)Q_R^{i**} - (p_o^{**} - v)Q_{OM}^{i*} \\ &\quad + p_e C\end{aligned}$$

for any market scenario i ($i = NR, N, R, O$). Here, Q_N^{i**}, Q_R^{i**} and Q_{OM}^{i*} are defined analogously to those under the carbon tax policy. The profit function of the firm under cap and trade reveals a structure similar to that under carbon tax policy except for the last term. Notice that the firm can gain a free emissions quantity C under the cap and trade. When emissions permits can be traded in the market, the manufacturer may gain additional revenue from selling extra permits compared with the situations under the carbon tax policy. We summarize the impacts of the cap and trade on the manufacturer's profits as follows.

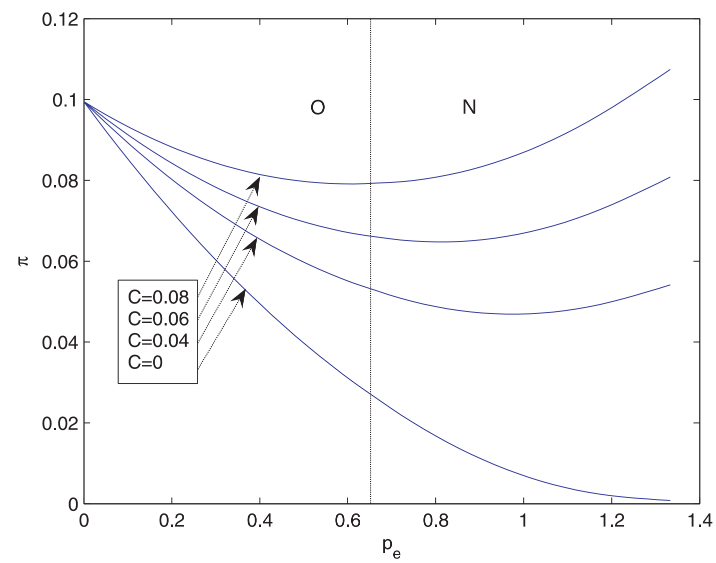
Proposition 5. *Under the cap and trade system, we have*

(i) $\partial\pi_C^{i*}/\partial C > 0$ for $i = NR, N, R, O$;

(ii) *for scenario NR and scenario R,* $\partial\pi_C^{NR*}/\partial s > 0$ *and* $\partial\pi_C^{R*}/\partial s > 0$ *if* $s > c_r + e_r p_e - v - (\delta_r - \delta_o)$, *and* $\partial\pi_C^{NR*}/\partial s \le 0$ *and* $\partial\pi_C^{R*}/\partial s \le 0$ *otherwise*;



(a) scenario NR and scenario R



(b) scenario N and scenario O

Fig. 3. The profit of the manufacturer π with respect to the carbon permit price p_e and the subsidy s in four scenarios, where c_n=0.4, c_r=0.3, e_n=0.4, e_r=0.25, $\delta_r = 0.7$, $\delta_o = 0.5$, ν=0.2, $\alpha = 0.5$, s=0.28 for the former case and s=0.19 for the latter case.

(iii) *for scenario N and scenario O,* $\partial\pi_C^{N*}/\partial s > 0$ *and* $\partial\pi_C^{O*}/\partial s > 0$ *if* $s > c_n + e_n p_e - \nu - (1-\delta_o)$, *and* $\partial\pi_C^{N*}/\partial s \le 0$ *and* $\partial\pi_C^{O*}/\partial s \le 0$ *otherwise.*

The proof is similar to that of Proposition 6 and the details are therefore omitted.

In fact, the major difference between carbon tax policy and cap and trade regulation is largely due to the free emissions cap C distributed by the government. As this proposition indicates, under certain conditions, the manufacturer can benefit from the subsidy of the government and its profits are increasing in the subsidy s. *In particular, when C=0, the cap and trade regulation is the same as the carbon tax policy.* Therefore, under the cap and trade regulation, it also can be shown that the subsidy improvement can promote the profit performance of the manufacturer without increasing the total carbon emissions. However, whether the manufacturers profits are increasing or decreasing in the permit price indeed depends on both the permit price and the emissions cap as well as other parameters. But the exact conditions are rather complex. For example, when the permit price is very high and dominates other parameters, the manufacturer may sell all of its permits and does not produce anything at all. However, when the permit price is relatively low, the manufacturer's profits may be increasing or decreasing in the permit price, depending jointly on the permit price and emissions cap.

We again provide a numerical example to illustrate the impacts of cap and trade more concretely. Similarly, these figures consider situations where the firm does not have the remanufacturing cost advantage but does have the emissions advantage. In contrast to the case of carbon tax, the firm's profits under cap and trade are increasing in the cap C. When C is relatively small (for example, C=0.14 and C=0.15 in Fig. 3(a) or C=0 in Fig. 3(b)), the profits are decreasing in the permit price. However, when C is sufficiently large (for example, C=0.16 and C=0.17 in Fig. 3(a) or C=0.06 and

C=0.08 in Fig. 3(b)), profits are decreasing in the permit price when it is relatively low but are increasing in the permit price when it is relatively high. This means that raising the permit price actually may boost the firm's profits under certain values of C. This can be interpreted as the additional revenue under cap and trade, which is determined jointly by the cap C and the permit price p_e. When the cap is large enough, the manufacturer can sell extra permits for additional profit. Thus, the higher the permit price p_e is, the more benefits the firm can potentially gain through selling the extra permits. As a result, the firm's profits may increase when the permit price p_e is sufficiently high.

5. Conclusion

In this paper, we address remanufacturing with trade-ins under the carbon tax policy and the cap and trade system. We analyze the firm's optimal pricing and production decisions under these carbon regulations. We develop analytical and numerical results that demonstrate useful insights for the firm and the government to use to make informed decisions in order to achieve sustainability. When carbon regulations are absent, we divide the demand markets into four scenarios in terms of the remanufacturing cost of the firm and the subsidies of the government. Under the trade-in policy, the firm tries to maximize its profits by proper production allocations between the new and remanufactured products. However, with the introduction of carbon regulations, the results become more complex. In this context, the demand markets are determined by the tax rate under the carbon tax policy or the permit price under the cap and trade policy and the subsidies of the government. Intuitively, the imposition of carbon regulations increases the prices of both new and remanufactured products. Although carbon regulations generally reduce demands of the new products and hurt the firm's overall profit, they do promote the sales of remanufactured products under certain conditions because remanufactured products produce less emissions in the process of production and therefore may provide more competitive advantages compared with new products when the carbon regulations are introduced. As for the manufacturer, it may have different strategies based on its costs and emissions advantages. The firm who has both costs and emissions advantages always produces remanufactured products for the new market and the replacement market under high subsidies, and only for the new market under low subsidies regardless of the tax rate. The firm who has emissions advantages but not costs advantages would produce remanufactured products for both the new market and the replacement market when the subsidies and the tax rate are both sufficiently high. From the perspective of the market, the demands of both the new market and the replacement market decrease with the introduction of carbon regulations. As a result, the manufacturer's profits are hurt by the carbon regulations. Nevertheless, through proper government subsidy schemes (i.e., increase in subsidy with the implementation of the carbon regulations), the manufacturer's profits can be improved. Furthermore, we also show the government has the incentive to propose the subsidy improvement scheme because under well-designed regulations total emissions can be reduced without hurting the firm's profits. Finally, in contrast to the situation under the carbon tax policy, the cap and trade program may improve the profit performance of the firm as it can offer free emission permits so that the firm may gain profits from selling extra permits. But some other research also proposes that these permits should be distributed by trade or auction [6,26]. In these contexts, cap and trade programs may not increase the firm's profits any more.

This paper may shed a light on remanufacturing systems with trade-ins under the carbon regulations. There are several directions worth further exploring. First, this study assumes the productions of the new and the remanufactured products are independent. In practice, they may be interrelated. So it is meaningful to relax this assumption in future study. Also, as an important link of remanufacturing, recycling is not explicitly considered in this paper. Further research also can incorporate recycling and formulate the model from the point of view of closed-loop supply chain and/or product life cycles. Another future research direction is to model the problem in a dynamic setting, i.e., the trade-ins in the first period will affect the production in the second period. In this case, the associated pricing strategies will be inevitably different and the analysis may require much different techniques. Finally, a number of traditional supply network design problems may be revisited with remanufacturing and carbon regulations taken into consideration.

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